Because of ever-shrinking IC geometries, the operating voltages in evolving systems are on a downward trend. For digital ICs, the 3.3V norm is rapidly displacing the classic 5V level; 3.3V will in turn succumb to even lower values. The lower voltages, however, provide little relief for power dissipation: Megamillion-transistor ICs and higher switching frequencies require more and more current. Power-supply manufacturers are hard-pressed to keep up with the dropping voltages and escalating currents. Switching-type dc/dc converters, once the clear choice for 5V systems, suffer lower efficiency at lower voltages. Low-dropout (LDO) linear regulators, with their modest filtering requirements, often become more attractive at lower voltages. Sometimes, combining a switcher and an LDO regulator makes more sense. Faced with these options, you can make your decision easier by first considering such factors as power, board area, noise, and cost.

The choice between linear and switching board-level power supplies is sometimes clear-cut. But as current demands rise and operating voltages sink, you must consider such factors as power wastage, filtering needs, available board space, and economics.

The major power consumer in computer systems is, and probably will remain, the "core" in the μP (or μPs, in multiprocessor systems). Fast μPs consume upwards of 15A at 2V or thereabouts; what can you expect in the future? Taking a stab in the dark, assume that a future μP will require 100A at 1V. Providing power with any degree of efficiency for such a 100W device will be a daunting task. A ±5% power-supply tolerance, for example, would allow only ±50-mV error in the 1V level. The 100A current drain would produce appalling losses in any rectification configuration today. Finally, the tremendous current fronts in such a μP will require an enormous reservoir of capacitors. (**References 1** and **2** explore some of the aspects of low-voltage, high-current power sources.)

Several types of losses occur in the rectification section of a buck-type step-down regulator (**Figure 1**). The switches in this circuit could simply be Schottky diodes or, for greater efficiency, power MOSFETs. As an example, assume a 50% switching duty cycle and 0.1Ω resistance in S_1, S_2, and L_1. Also assume a 2A average load current at 1V; I_{AVG} is thus 1A. The I^2R loss in each switching element is 0.1W; in the inductor, it's 0.4W. More losses (assume another 0.1W) occur in the finite turn-on and -off intervals for the switches. Total rectification losses thus total 0.7W for 2W load power; efficiency (η) equates to 74%. This simplified analysis does not even include the power losses in the ESR of the output capacitor or the power dissipated in the controller IC.

Now, consider the futuristic scenario of 100A, 1V. Series resistance of 0.1Ω in the switches and inductor would produce the absurd loss figures of 250W in each switch, and 1000W in the inductor. Switches and inductors with series resistance lower than 0.1Ω are, of course, available. However, keeping the switch and inductor losses to reasonable levels at 100A load current is still a formidable challenge. The I^2 term in the inductor is 10,000A^2. Dissipation of 10W in the inductor, for example, mandates a 1-mΩ series resistance. Dissipation of 10W in each switch entails 4-mΩ series resistance, approximately the current state of the art in power MOSFETs. However, trace and connection resistances inevitably add several more milliohms to the inductor resistance and the intrinsic MOSFET on-resistance.

Largely because of the rectification losses, the efficiency of a step-down dc/dc converter decreases with decreasing output voltage. As an example, **Figure 2**, which is derived from the characteristic curves for the Power Trends PT6305 Series of 3A integrated switching regulators, shows the efficiency dropping from approximately 79% for a 3.3V-output model to 56% for a 1.2V-output device. Extrapolating the curve to 1V yields 53% efficiency. Rearranging the efficiency equation, $\eta = P_{OUT}/(P_{SUPPLY}+P_{OUT})$, $P_{SUPPLY} = P_{OUT}(1/\eta - 1)$. With 3W output, an η of 53% yields 2.67W dissipation in the dc/dc converter. The same efficiency for a future 100A, 1V load produces 88.7W dissipation in the converter.

Linear or switcher or both?

It would seem intuitively obvious that a switching regulator is always more power-efficient than a linear regulator. Intuition notwithstanding, that's not necessarily always true. **Figure 3** gives expressions for the approximate regulator power for a linear regulator (a) and a switching convert-

Thermal management, using a copper-plated ceramic substrate, yields small size and high efficiency in Ericsson's PKG 46W dc/dc converters.

er (**b**). The equations are approximations, because they don't take account of the operating currents of the regulators. However, for high-current supplies, these quiescent currents are negligible in comparison with the load currents. Imagine a 100A, 1V system again. If you use an LDO regulator with a 0.4V dropout voltage at the regulator's dropout limit (with a 1.4V input), the efficiency of the regulator is 71%. This figure is higher than that attainable from a switching regulator (for such a low output voltage), *but* the linear regulator must obtain the 1.4V input via a switching regulator.

The power that a switching regulator dissipates is a function of its efficiency (**Figure 3b**). Note, however, that the efficiency for a converter is also a function of the input-output differential. The converters use PWM for regulation, so the switching duty cycle is a function of the differential. The losses in the rectification section are, in turn, a function of the switching duty cycle. In some situations, you may find that a tandem switcher-linear configuration provides several advantages (**Figure 4**). First, for extremely low output voltages, a switcher has low efficiency. Second, using a linear postregulator eases filtering and smoothing burdens and thus allows the use of much smaller capacitors.

Figure 4 gives the approximate power-dissipation figures for the switching and linear sections, as well as the total dissipation in both blocks. Note that the total power dissipation is a function of only the intermediate voltage, V_I, and the switcher's efficiency figure, η. The equations in **Figure 4** enable you to perform "what-if" exercises. If you set up a simple spreadsheet (using Lotus 1-2-3 or Excel, for example), you can see the effects of choosing various intermediate-voltage values on power sharing and on total power dissipation.

Figure 5 shows a two-stage approach. The composite circuit is a 12-to-3.3V converter that supplies 14A peak to logic circuitry. The overall efficiency of the tandem is 72%. The LT1575 controller uses an International Rectifier (El Segundo, CA) IRLZ44 power MOSFET as the pass transistor, yielding less than 550-mV dropout voltage. The switching regulator's output (the intermediate voltage) is 4V. Though the circuit in **Figure 5** seems heavily laden with capacitors, its two-step approach sharply eases the amount and type of capacitors required in a switching-only approach. The 1000-μF electrolytics at the switcher's output need not be expensive, low-ESR tantalums, and the 0805 multilayer ceramic capacitors (MLCs) at the linear regulator's output are inexpensive and area-efficient. Perhaps most important, the linear regulator's output stage delivers fast transient response to high-current load steps.

@a glance

- The switching/linear efficiency gap shrinks as voltages decrease.
- A two-stage approach sharply reduces capacitor demands.
- Efficiency takes a back seat to quietness in wireless systems.
- CMOS switches and flying capacitors make efficient converters.

The LT1575's dropout voltage is entirely a function of the $R_{DS(ON)}$ of its external, n-channel MOSFET pass transistor. Using new-generation MOSFETs with $R_{DS(ON)}$ of only a few milliohms, you can configure regulators with dropout voltages much lower than 0.1V. A pnp pass transistor also provides LDO voltage, but its disadvantage is the hefty base current (I_{LOAD}/beta) that flows to ground. The n-channel MOSFET also provides high bandwidth and responds to load transients in only a few hundred nanoseconds vs the many microseconds for a bipolar pass transistor.

Because it uses an n-channel MOSFET as a pass element, the LT1575 requires a separate supply that's several volts higher than the MOSFET's source voltage to provide the gate drive. A new LDO controller from National Semiconductor gets around that requirement by using an external p-channel MOSFET. The $0.98 (1000) LP2975 can deliver 1A output current with less than 0.1V dropout voltage. In a typical application, the LP2975 can operate with voltages from 1.8 to 24V (**Figure 6**). Its current drain is typically 180 μA in

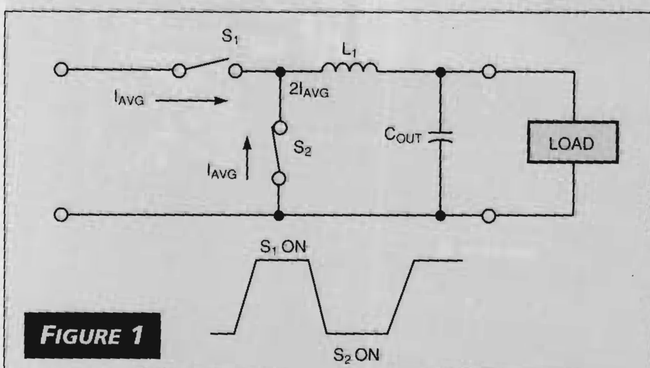


FIGURE 1

A buck-type step-down converter incurs losses in the on-resistances of the switches, the series resistance in the inductor, the ESR of the output capacitor, and the switching transitions.

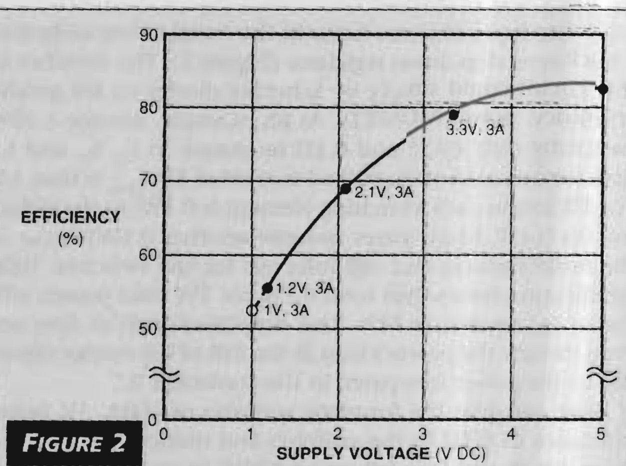
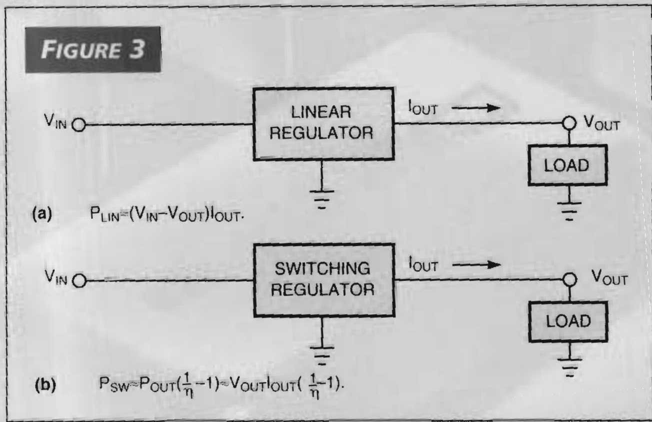
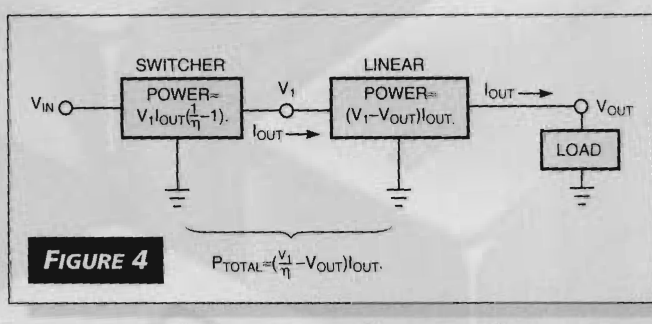


FIGURE 2

Because of rectification losses, the efficiency of a switching dc/dc converter dwindles as the output voltage decreases.



Approximations of the power dissipation in a linear (a) and switching (b) regulator ignore the regulators' quiescent current, which is negligible for high-current supplies.



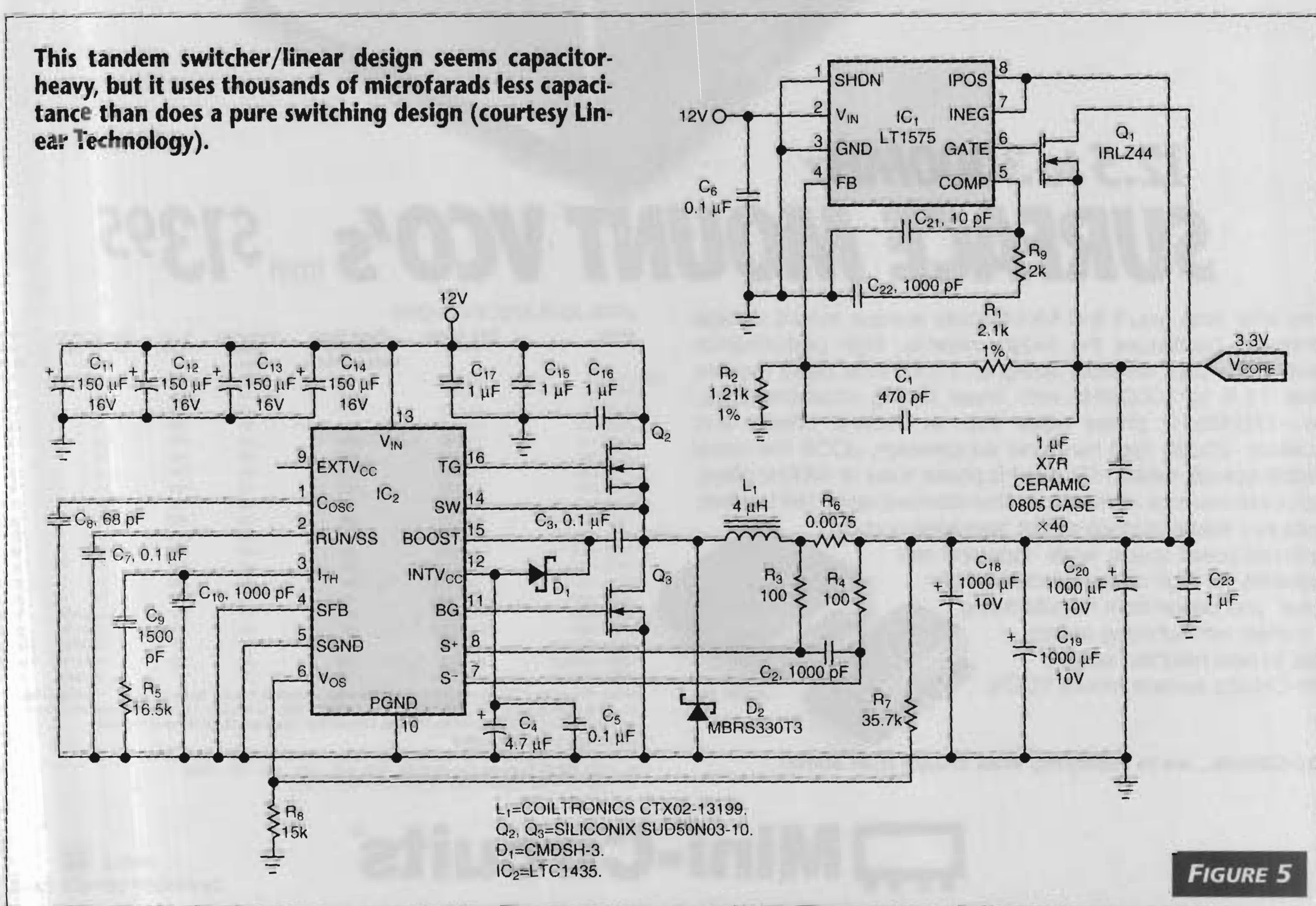
In a tandem switcher/linear configuration, the power does not vary with input voltage, except insofar as the input level affects the efficiency of the switcher.

operating mode and less than 1 μA in shutdown mode.

A 3A LDO regulator from Unitrode also provides fast response to current transients. The \$5.85 (1000) UC182 family, available with 1.5, 2.1, 2.5, and adjustable output voltages, is suitable for driving GTL and BTL (Gunning- and backplane-transceiver-logic) buses, for example. The device requires one electrolytic capacitor at its input and an electrolytic and an MLC at its output. **Figure 7** shows the output-voltage transient response to a current step of 10 mA to 3A. Dropout voltage is 450 mV maximum at 100°C and 350 mV typical at 25°C with a 3A load.

An LDO regulator from Semtech targets next-generation, 2.5/3.3V split-plane designs for Pentium MMX, IBM PowerPC 603EV/604EV, Cyrix (Richardson, TX) 6x86 MX, and AMD (Sunnyvale, CA) K6 μPs. The \$2.36 (1000) EZ1580 family offers models providing 1.5, 3, 5, and 7A output current. The devices use remote sensing to reduce errors in pc-board traces and other resistive losses between the regulator and processor. An associated circuit from Semtech, the EZ1900 controller, uses the processor's upgrade-pin level to deter-

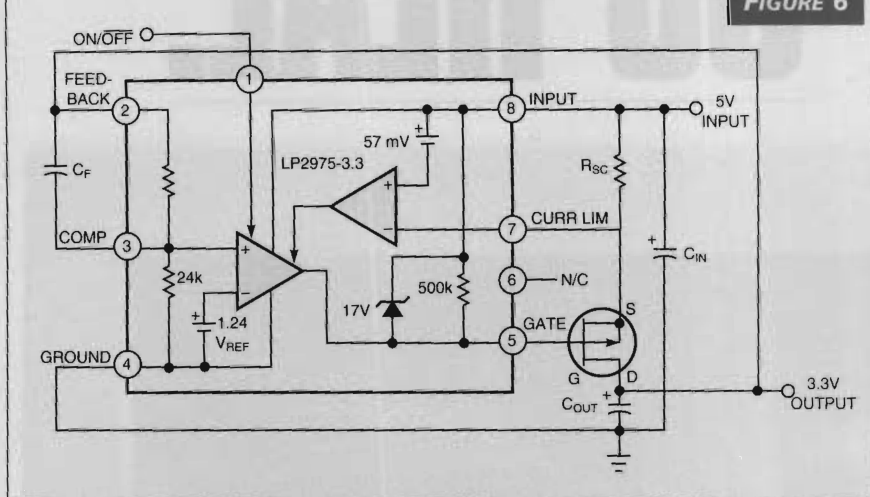
This tandem switcher/linear design seems capacitor-heavy, but it uses thousands of microfarads less capacitance than does a pure switching design (courtesy Linear Technology).



mine whether to tie the outputs of two EZ1580s together (for an all-3.3V processor) or to use them separately (for a processor with a 2.5V core and 3.3V logic).

In many applications, a linear regulator is a necessity because of noise considerations. For example, the baseband analog and synthesizer/VCO sections in wireless systems cannot tolerate any degree of glitchiness that exists in switching-supply outputs. **Reference 3** correctly points out that this glitchiness is not "noise" (that is, noncoherent, random components) but rather coherent, high-frequency residue that directly relates to the regulator's switching action. The MAX8867 and 150-mA MAX8868 linear regulators from Maxim (each $0.80 (1000)) combine low noise (30 μV rms) and low dropout (165 mA at 150 mA) for sensitive wireless applications.

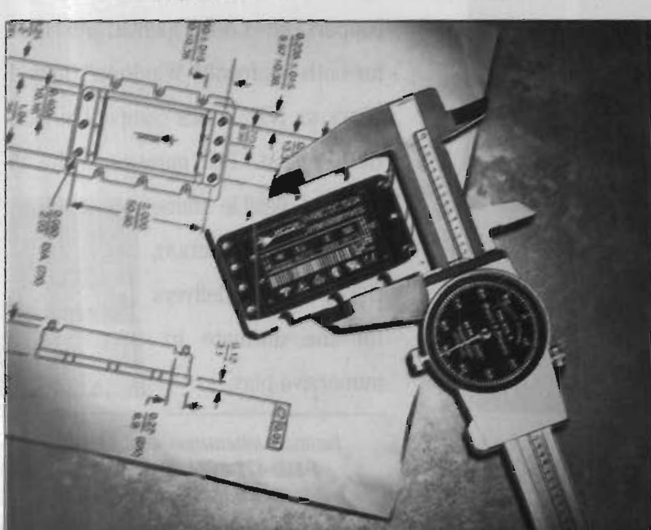
FIGURE 6



The use of a p-channel pass element in National Semiconductor's LP2975 LDO regulator eliminates the need for a second voltage supply or a charge pump to generate gate drive.

The Maxim devices use an internal p-channel MOSFET as a pass element in models that provide eight output voltages, from 2.5 to 5V. Operating current is 85 μA with no load and 100 μA when fully loaded. Features include short-circuit and thermal shutdown, reverse-battery protection, logic-controlled shutdown, and an autodischarge function (in the MAX8868), in which the output actively discharges the load to ground when the device goes into shutdown mode. Both devices come in five-pin SOT-23 packages.

Note that the question of efficiency in comparing switchers and linear regulators is sometimes unimportant. In a cellular phone, for example, it is important to have an efficient converter to supply the main power bus from the battery, but for low-level circuitry, efficiency is not a crucial issue. LDO regulators supply much of the noise-sensitive circuitry in a cellular phone, and this circuitry draws only a few microamps. Thus, the "inefficient" LDO regulators waste only a few microwatts.



An architecture using zero-voltage and -current switching yields low noise and 90W/in.³ power density in Vicor's 150W dc/dc converters.

Switchers get quieter

Most switching regulators require switching-noise-reduction techniques—bypass capacitors, ferrite beads, and shields—to suppress conducted and radiated noise. That's not the case with Linear Technology's LTC1533, a dc/dc converter that produces less than 100-μV p-p output noise. In a push-pull configuration that converts 5V to 12V, 200 mA, the $4.95 (1000) converter cuts noise by controlling the voltage and current slew rates of its two internal power switches (**Figure 8**). You can omit the second LC section in the output stage if some low-frequency ripple is acceptable in your application. The loop on Pin 16 is a 22-nH inductor, which provides compensation for the output-current control loop. This inductor can be a length of pc-board trace, a coiled wire, or a ferrite bead.

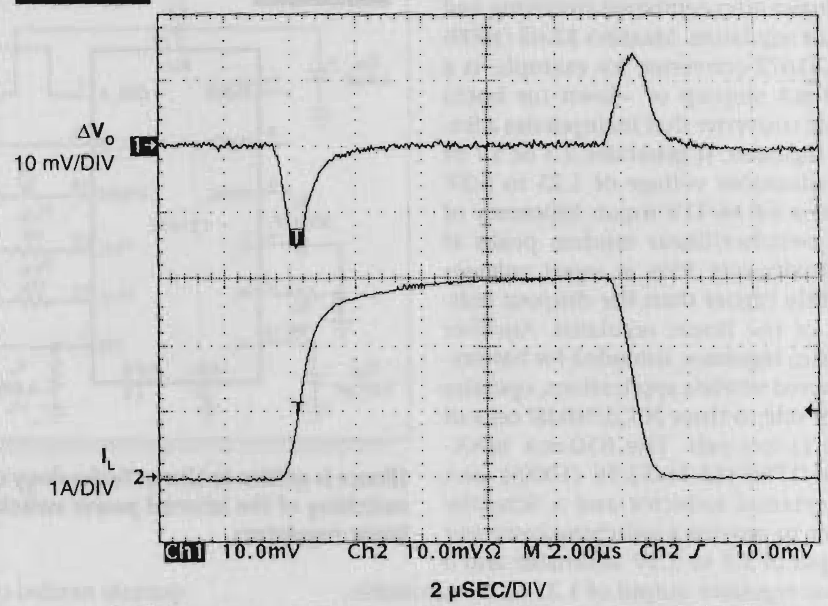
Reference 2 describes the monolithic switching regulators EL7563C and EL7556C from Elantec that incorporate the MOSFET power switches. The $5.71 (1000) HIP5020 from Harris also integrates the MOSFETs and steps a 4.5 to 18V input down to 3.3V or less at 3.5A load current. The only external components the device needs are the output inductor and capacitor, a Schottky diode from output to ground, and a diode for the bootstrap charge pump for the upper power MOSFET's gate drive. This last diode is necessary only if the input voltage is lower than 9V. The HIP5020 operates at switching frequencies from 100 kHz to 1 MHz. Characteristic curves for the regulator show efficiencies ranging from 85% at a 1-mA light load, to 96% at 1A, to 92% at 3.5A.

National Semiconductor continues to expand its Simple

LINEAR/SWITCHING SUPPLIES

Switcher family of step-down converters. The recent LM2672 and LM2675 1A switchers incorporate a 0.25Ω DMOS output switch and operate at 260 kHz to provide 3.3, 5, or 12V or a user-adjustable output level from an input of 8 to 40V. With 10V input, efficiency is 86% for a 3.3V output and 91% for a 5V output. Simple Switchers need one MLC, two electrolytic capacitors, an inductor, and a Schottky diode. It's easy to design a supply around these devices; National provides Windows-compatible design software, dubbed Switchers-Made-Simple. The software provides an application-specific component list using industry-standard passive-component values. The LM2672 differs from the LM2675 in that it provides a soft-start control line and a Sync pin that accommodates an external switching-frequency source. Prices are $3.45 and $3.22 (1000), respectively.

FIGURE 7



An LDO regulator is often the power supply of choice because of its fast transient response. Fast response keeps transient glitches smaller than 15 mV in response to a 3A current step in Unitrode's UC182 regulators.

For those who wish to configure their own switching regulator, several PWM controllers are available that use external power MOSFETs and passive components to provide efficient power conversion (References 1 and 2). Some recently introduced products provide several features that enhance ease of design and utility. Maxim's $3.85 (1000) MAX1638, for example, uses an Intel-specified (spec voltage-regulator module 8.2), 5-bit code to select output voltages from 1.3 to 3.5V. With appropriate external power MOSFETs, a MAX1638-based supply can furnish more than 35A output current. The device uses pin-selectable switching frequencies of 0.3, 0.6, or 1 MHz. A Glitch-Catcher feature allows you to tack on a couple of more MOSFETs to provide fast recovery from load transients. The additional MOSFETs eliminate delays accruing from the buck inductor.

Two new PWM controllers from Cherry Semiconductor incorporate features that minimize component count. The CS-5102X supplants the industry-standard 384X controller by integrating soft-start operation, bidirectional synchronization, slope compensation, and undervoltage and overvoltage monitors. The bidirectional-synchronization feature allows you to synchronize multiple controllers to the operating frequency of the fastest controller. Slope compensation prevents instability that can arise when duty cycles exceed 50%. Model CS-5106 integrates two PWM drivers. The $3.85 (10,000) chip hosts a dual n-channel FET that serves as the main supply controller and a single n-channel FET driver you can use for powering an auxiliary supply. The controllers operate independently, and each has its own current-limit and overvoltage-monitoring protection functions.

LOOKING AHEAD

The mixed-technology regulators are coming. Several regulators combine switching dc/dc converters and linear regulators, and it's a virtual certainty that the development of these mixed-topology supplies will accelerate. Wireless applications provide an overwhelming impetus for such development efforts. A cellular telephone, for example, uses several different types of power sources, both linear and switching.

A step-down (buck) converter provides the main power bus, derived from a Li-ion battery. Three low-dropout (LDO) regulators provide power for the receiver, the frequency synthesizer, and the low-level transmitter circuitry. A fast LDO regulator powers the phone's DSP block. A boost dc/dc converter steps up the bus voltage to power the transmitter's power-output stage. Finally, a charge-pump bias generator provides the negative bias for the GaAsFETs in the transmitter stage.

As is already happening in set-top boxes, disk drives, and other applications that use disparate-function ICs, it's likely that the separate power-supply blocks in wireless systems will merge. The convergence of the different-topology supplies onto a single chip will result in lower cost, higher volumetric efficiency, and enhanced reliability.

ous life testing. Line and load regulation are 10 and 35 mV, respectively, with 60-mV p-p ripple. Load-transient response is within 100 μsec. You can connect multiple PKG modules in parallel to obtain higher power. Ericsson's recent 6W PKF Series provides 1.2A at 5V with an input range of 18 to 72V. The $27.39 (500) devices are available in through-hole versions or in packages amenable to pick-and-place mounting machinery.

Finally, two recent ac/dc, front-end supplies are also noteworthy. The NLP40 ac/dc power supply from Computer Products provides 40W from a package having the smallest footprint in the industry at 2.5×4.24 in., according to the company. The device accepts universal inputs over the range of 90 to 264V ac and is available in single, dual, and triple models. A new TOPSwitch device from Power Integrations (Sunnyvale, CA) comes in an eight-pin, surface-mount package. The TOP209/210 is an IC that integrates a 700V power MOSFET with PWM and other control circuitry on the same chip. You can use the $0.89 (10,000) device to configure ac/dc supplies that deliver as much as 8W from a 100/115/230V ac input in a less than 15-cm² board area using only 12 components.

It's not easy to directly compare switching and linear regulators. The choice is often application-mandated because of factors including heat, available board area, noise, transient response, battery drain, and cost. Sometimes, the selection process hovers in a gray area, in which you could choose either technology. In that case, it might be wise to consult with an objective manufacturer—one that sells both switchers and linears.

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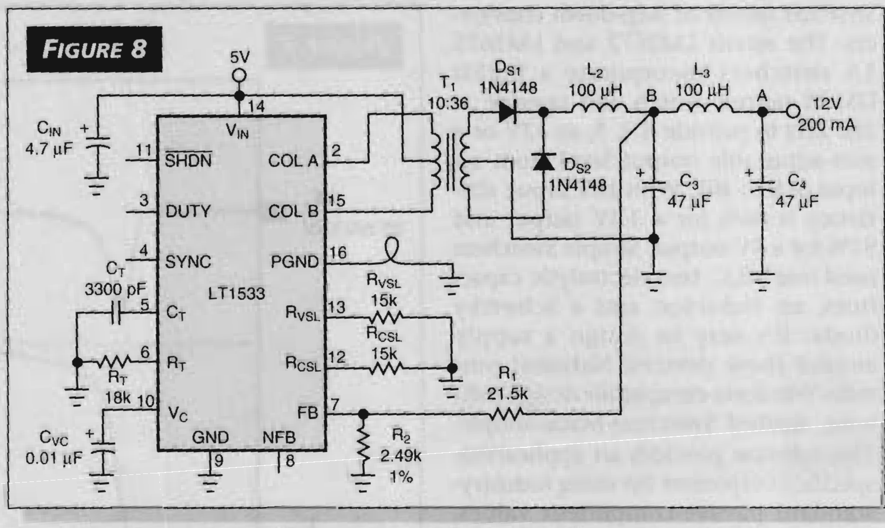
In keeping with the philosophy of the two-step approach, some IC manufacturers offer combined switching and linear regulators. Maxim's \$2.65 (1000) MAX1672 converter, for example, is a 300-mA step-up or -down (or both) dc/dc converter that incorporates a linear regulator. It generates 3.3 or 5V or an adjustable voltage of 1.25 to 5.5V from a 1.8 to 11V input. Efficiency of the switcher/linear tandem peaks at approximately 95% at input voltages slightly higher than the dropout voltage of the linear regulator. Another Maxim regulator, intended for battery-powered wireless applications, operates from one to three NiCd/NiMH cells or one Li-ion cell. The 850-mA MAX-1705/1706 (\$3.15/\$2.96 (1000)) uses an external inductor and a Schottky diode to provide a switching-converter output of 2.5 to 5.5V adjustable and a linear-regulator output of 1.25 to 5V adjustable.

FIGURE 8



Silence is golden in Linear Technology's LT1533 switching-regulator controller. Soft switching of the internal power switches keeps the noise lower than that of many linear regulators.

A switching/linear combo from Semtech comes in a seven-pin TO-220 package, in four versions that supply 1.5 to 7.5A. The switching section uses the usual external power MOSFET, Schottky diode, and passive components to provide a user-programmable high-current, low-voltage output. The linear section uses an npn pass transistor to provide 1%-accurate output voltages of 1.5, 2.5, or 3.3V. Dropout voltage is typically 0.8V for versions that supply 5A or less and 1.3V for the 7.5A version.

One attribute of CMOS is responsible for the development of a class of inductorless dc/dc converters. CMOS makes good switches, and by switching charges between capacitors, it's possible to make voltage multipliers, dividers, and polarity inverters. ICs using this switched-capacitor, charge-pump topology provide compact, low-cost supplies for a variety of applications. Maxim's \$1.60 (1000) MAX619, for example, uses two 0.22-µF flying capacitors and two electrolytic capacitors to provide a regulated, ±4%-accurate, 5V output from a 2 to 3.6V input range. The low input-voltage range makes the device suitable for portable applications.

The \$2.95 (1000) MAX660 from Maxim can operate either as an inverter—producing –1.5 to –5.5V from a corresponding positive input—or as a doubler—providing 9.35V at 100 mA from a 5V input. You can select either a 10- or an 80-kHz switching frequency to optimize the required capacitor size and IC quiescent current. The device has 88% typical efficiency at 100-mA output current. Linear Technology's LTC1515 switched-capacitor converter uses four NiCd cells to generate a ±4%-accurate, 3.3 or 5V, 50-mA output. It uses one MLC and two electrolytic capacitors. The device also uses soft-start circuitry to eliminate the high inrush currents inherent in most switched-capacitor ICs upon power-up.

A unique switched-capacitor converter from National Semiconductor provides a fractional 3-to-2 or 2-to-3 output/input ratio. The \$1.19 (1000) LM3350 provides the frequently needed conversion of 3.3 to 5V or 5 to 3.3V. Housed in a mini-SO8 package, the device provides 50 mA with efficiency greater than 90%. Its 800-kHz operating frequency allows the use of small and inexpensive 0.33-µF capacitors. A low-current shutdown mode disables the IC and reduces the quiescent current to 25 nA.

Many RF stages in wireless systems use GaAsFETs. These transistors require a negative bias voltage, and switched-capacitor converters are ideal for supplying this bias. Maxim's 4-mA MAX840/844 (\$1.75 (1000)), for example, offers both a preset –2V output and a –0.5 to –9.4V adjustable output. Input range is 2.5 to 10V. The converter uses capacitors with values as low as 0.22 µF. Linear Technology's \$2.60 (1000) LTC1550 also targets GaAsFET applications; it provides an adjustable –1.5 to –4.5V output from a 2.7 to 6.5V input. Another version provides a fixed –4.1V output. The converter's 900-kHz switching frequency allows using 0.1-µF flying capacitors and keeps ripple below 1 mV.

Modules make inroads

You can often obtain the optimum performance, volumetric efficiency, and cost by building your own power supplies. In many applications, however, self-contained, off-the-shelf power modules may offer the best way to go. Vicor, for example, progenitor of the "Vicor footprint" in the 1980s, continues to shrink packages and increase power density. The V48C12C150A family (\$112 (unit)) produces 150W output in a 57.9×36.8×12.7-mm package, for a 90W/in.^{3} power density. Like all Vicor supplies, this module uses zero-current switching (ZCS) and zero-voltage switching (ZVS) to reduce input conducted noise and output ripple.

The PKG 2410 PI from Ericsson provides 3.3V at 14A from a 24V input bus. The \$60 (500) module requires no heat sinking at ambient temperatures to 60°C. The company claims greater than 200-year MTBF, a claim backed up by continu-

(continued on pg 54)